

# Firefighters' Physiological Responses to Boot Weight and Sole Flexibility during Ladder Climbing and Obstacle Crossing

N. Turner,<sup>1</sup> S. Chiou,<sup>2</sup> J. Zwiener,<sup>2</sup> D. Weaver,<sup>2</sup> and W. Haskell,<sup>1</sup>

<sup>1</sup> National Personal Protective Technology Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA

<sup>2</sup> Division of Safety Research, National Institute for Occupational Safety and Health, Morgantown, WV

## Abstract

PURPOSE: Firefighter boots may be composed of rubber (R), lighter leather (L), or ultralight fabric/leather hybrid (H). Boot soles can be stitched (S, less flexible) or cemented or bonded (F, more flexible). A 5 to 12% increase in oxygen consumption per kg of weight added to the foot has been observed; however, this increase may depend on boot weight and sole flexibility. METHODS: Fourteen women and 14 men, while wearing full turnout clothing, a 10.5-kg backpack, gloves, helmet, and one of four randomly assigned pairs of firefighter boots (HS, LS, LF, RF) walked for five minutes at approximately 0.57 m sec<sup>-1</sup> while stepping over two 15-cm and two 30-cm obstacles and carrying a 9.5-kg hose and climbed up and down a 3.7-m ladder for five minutes at 25 rungs per minute. Minute ventilation (VE), oxygen consumption ( $\text{VO}_2$  and  $\text{VO}_2/\text{kg}$ ),  $\text{CO}_2$  production ( $\text{VCO}_2$ ), and heart rate (HR) were measured, and an average of the breath-by-breath data from minute five was used for analysis. RESULTS: During obstacle crossing, increased boot weight significantly increased VE,  $\text{VO}_2$ ,  $\text{VO}_2/\text{kg}$ , and  $\text{VCO}_2$  ( $p < 0.05$ ). There were significant decreases in  $\text{VO}_2/\text{kg}$  (men and women) and in  $\text{VO}_2$  and  $\text{VCO}_2$  (women only) for less flexible compared to more flexible soles ( $p < 0.05$ ). During ladder climbing, boot weight had a significant effect ( $p < 0.05$ ) on  $\text{VO}_2$  and  $\text{VO}_2/\text{kg}$ , but there were no significant effects of sole flexibility. CONCLUSION: There were significant effects of boot weight on metabolic variables (5–11% increases per one kg increase in boot weight) during both obstacle crossing and ladder climbing, which were mitigated by sole flexibility (5–6% decrease for less flexible compared to more flexible soles) for obstacle crossing only.

## Introduction

The intensity of energy expended by firefighters performing fire fighting tasks is generally agreed to be in the heavy to very heavy range. According to the National Fire Protection Association (NFPA), an estimated 79,700 firefighter injuries occurred in the line of duty in 2008.<sup>(1)</sup> The top two leading causes of injury were overexertion (23.1%) and falls (23.5%). Of all 103 firefighter fatalities in 2008, 41 were the result of exertion/stress.<sup>(2)</sup> There are two general types of certified structural fire fighting boots in use today: 13"-16" rubber bunker boots and 8"-16" leather or leather/fabric "hybrid" boots. Leather boots are produced with either stitched or cement soles. During treadmill walking, a 3–10% increase in oxygen consumption per kg increase in boot weight has been observed;<sup>(3)</sup> however, a 4–5% decrease in  $\text{VO}_2$  has been observed when stitched-soled boots were compared to cement-soled.<sup>(4)</sup> The purpose of the current study was to determine the effects of boot weight and sole flexibility on men and women firefighters' metabolic variables during simulated firefighting tasks with trip/fall potential.

## Methods

Fourteen men and 14 women (100% professional) firefighters between the ages of 18 and 40 were recruited and provided informed consent for this study. Men (mean age 28 yrs, wt 94 kg, ht 178 cm) were recruited from the Morgantown, WV area, while women (mean age 33, wt 68 kg, ht 167 cm) were recruited from West Virginia, western Maryland, northern Virginia, and eastern Ohio. All subjects, while wearing full turnout clothing, a 10.5-kg backpack, gloves, helmet, and one of four randomly assigned pairs of NFPA-certified firefighter boots, walked for five minutes at approximately 0.57 m sec<sup>-1</sup> while stepping over two 15-cm and two 30-cm obstacles and carrying a 9.5-kg hose (Fig. 1), and climbed up and down a 3.7-m ladder for five minutes at 25 rungs per minute (Fig. 2). Boot models and characteristics are shown in Table 1. Boot longitudinal stiffness testing was performed by SATRA (Northhamptonshire, UK), and boots with a maximum flex angle <50° and stiffness index >15.0 were classified as less flexible (HS and LS), while boots with a maximum flex angle ≤50° and stiffness index ≤15.0 were classified as more flexible (LF and RF). Task order was randomized for each pair of boots. Minute ventilation (VE), oxygen consumption ( $\text{VO}_2$  and  $\text{VO}_2/\text{kg}$ ),  $\text{CO}_2$  production ( $\text{VCO}_2$ ), respiratory quotient (R), and heart rate (HR) were measured using a portable metabolic measurement system (COSMED, Italy), and an average of the breath-by-breath data from minute five was used for analysis. Boot weight and sole flexibility effects were analyzed using a MIXED procedure (SAS).

Table 1. Boot models and characteristics.

Model	Sole Type	Weight	Max Angle	Stiffness Index	Height	Heel Area
HS	Hybrid/Stitched	2.5 kg men 2.0 kg women	<50°	15.6	36.8 cm	84.6 cm <sup>2</sup>
LS	Leather/Stitched	2.9 kg men 2.5 kg women	<50°	19.2	36.6 cm	83.2 cm <sup>2</sup>
LF	Leather/Flexible	3.1 kg men 2.6 kg women	50°	6.8	30.2 cm	82.6 cm <sup>2</sup>
RF	Rubber/Flexible	3.8 kg men 3.4 kg women	<50°	12.8	39.4 cm	71.6 cm <sup>2</sup>

## Results

During obstacle crossing, significant boot weight effects ( $p < 0.05$ ) were observed for VE,  $\text{VO}_2$ ,  $\text{VO}_2/\text{kg}$ , and  $\text{VCO}_2$  in both men and women (Table 2). Significant effects of sole flexibility ( $p < 0.05$ ) were observed for  $\text{VO}_2/\text{kg}$  (men and women) and in  $\text{VO}_2$  and  $\text{VCO}_2$  (women only). During ladder climbing, significant boot weight effects ( $p < 0.05$ ) were observed for  $\text{VO}_2/\text{kg}$  in both men and women and for  $\text{VO}_2$  in men only (Table 3). There were no significant effects of sole flexibility.

Table 2. Mean (SD) obstacle crossing results for men and women.

Boot	VE (L/min, BTPS)	$\text{VO}_2$ (L/min, STPD)	$\text{VO}_2/\text{kg}$ (ml/kg/min, STPD)	$\text{VCO}_2$ (L/min, STPD)	R	HR (bpm)
Men (n=14)						
HS	50.8* (9.0)	1.75* (0.25)	19.0* (2.1)	1.41* (0.25)	0.80 (0.06)	157 (24)
LS	52.1* (8.6)	1.81* (0.26)	19.6* (2.0)	1.44* (0.24)	0.79 (0.05)	160 (24)
LF	51.0* (8.8)	1.71* (0.21)	18.7** (2.8)	1.35* (0.18)	0.79 (0.05)	160 (28)
RF	54.9* (7.0)	1.89* (0.26)	20.5** (2.6)	1.53* (0.24)	0.81 (0.06)	158 (23)
Women (n=14)						
HS	49.7* (8.7)	1.57* (0.23)	23.3* (2.2)	1.31* (0.26)	0.83 (0.07)	159 (27)
LS	49.3* (8.1)	1.60* (0.23)	23.8* (2.7)	1.32* (0.22)	0.82 (0.06)	157 (20)
LF	49.1* (9.2)	1.54** (0.26)	22.8** (3.3)	1.24** (0.23)	0.81 (0.07)	163 (23)
RF	51.8* (9.0)	1.61** (0.24)	23.9** (2.4)	1.33** (0.24)	0.83 (0.06)	163 (20)

\* Significant ( $p < 0.05$ ) effect of boot weight

\*\* Significant ( $p < 0.05$ ) effect of boot weight and sole flexibility



Fig. 1 Obstacle crossing.

Table 3. Mean (SD) ladder climbing results for men and women.

Boot	VE (L/min, BTPS)	$\text{VO}_2$ (L/min, STPD)	$\text{VO}_2/\text{kg}$ (ml/kg/min, STPD)	$\text{VCO}_2$ (L/min, STPD)	R	HR (bpm)
Men (n=14)						
HS	50.2 (10.6)	1.84* (0.30)	20.0* (2.7)	1.41 (0.28)	0.76 (0.06)	155 (23)
LS	52.1 (9.8)	1.95* (0.35)	21.0* (2.1)	1.48 (0.29)	0.75 (0.05)	160 (19)
LF	51.4 (9.2)	1.89* (0.40)	20.4* (3.5)	1.47 (0.33)	0.78 (0.04)	159 (25)
RF	52.9 (9.5)	1.98* (0.36)	21.5* (3.2)	1.52 (0.29)	0.77 (0.06)	156 (21)
Women (n=14)						
HS	44.5 (8.7)	1.59 (0.26)	23.5* (1.9)	1.23 (0.19)	0.77 (0.04)	158 (24)
LS	44.7 (8.9)	1.62 (0.26)	23.9* (2.4)	1.27 (0.22)	0.79 (0.04)	155 (21)
LF	47.5 (8.8)	1.62 (0.26)	23.9* (2.6)	1.25 (0.19)	0.78 (0.05)	161 (22)
RF	48.3 (10.4)	1.63 (0.24)	24.2* (2.2)	1.29 (0.21)	0.79 (0.05)	160 (23)

\* Significant ( $p < 0.05$ ) effect of boot weight

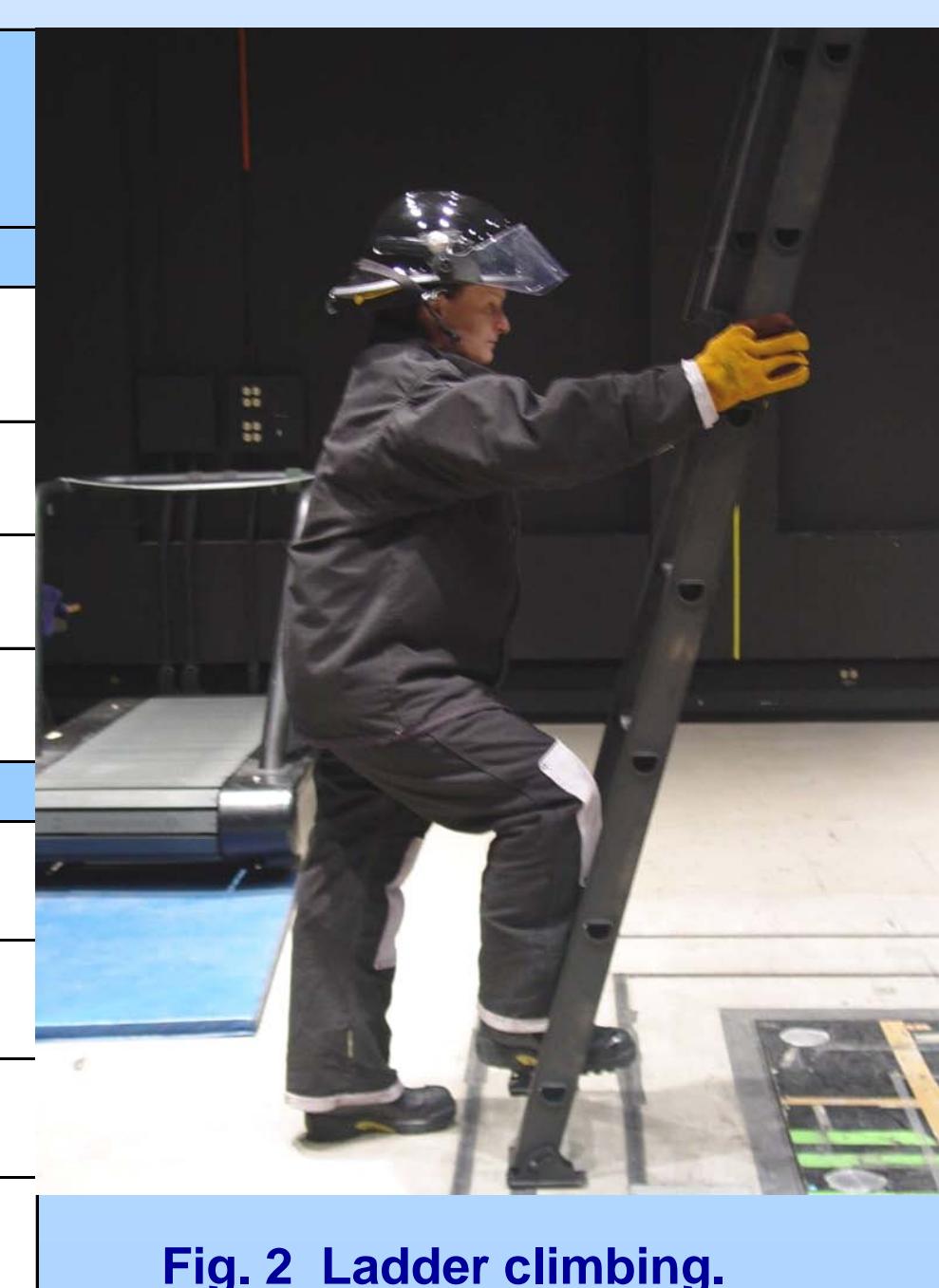


Fig. 2 Ladder climbing.

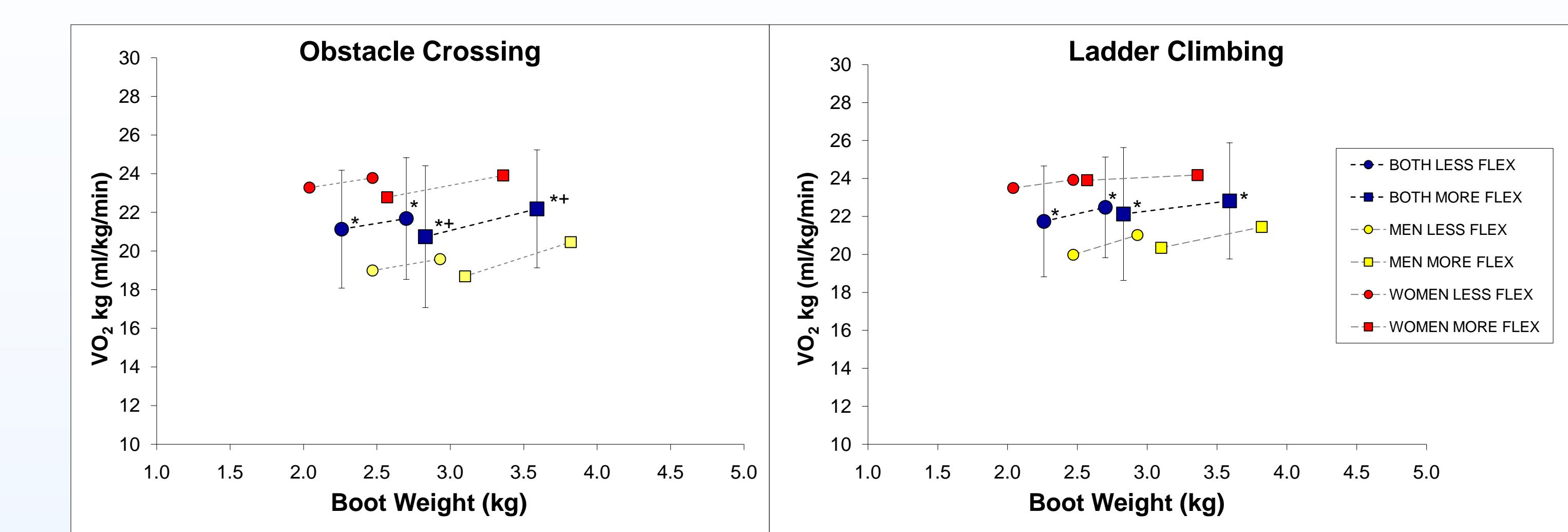


Fig 3. Main effects of boot weight (\*) and sole flexibility(+) on  $\text{VO}_2/\text{kg}$  for both tasks ( $p < 0.05$ ).

Table 4 shows the estimated percent change in metabolic and respiratory variables due to boot weight and sole flexibility for each task. A 7% increase in VE per one kg increase in boot weight, observed in men and women during obstacle crossing, would result in an approximate 3 minute decrease in service time for a 45-min SCBA cylinder. For oxygen consumption per kg body weight, significant increases per one kg increase of boot weight of 8.7% for men and 7.1% for women were estimated. However, for less flexible compared to more flexible soles, decreases in relative oxygen consumption of -6.1% for men and -5.0% for women were observed.

Table 4. Estimated percent change due to boot weight and sole flexibility.

Task	Estimated Percent Change per 1 kg Increase in Boot Weight					Estimated Percent Change for Less Flex Compared to More Flex Sole				
	VE (L/min, BTPS)	$\text{VO}_2$ (L/min, STPD)	$\text{VO}_2/\text{kg}$ (ml/kg/min, STPD)	$\text{VCO}_2$ (L/min, STPD)	HR (bpm)	VE (L				